Acquiring Real World Spatial Skills in a Virtual World

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Summary

In rehearsing specific missions, soldiers frequently must learn about spaces to which they have no direct access. Virtual Environments (VE) representing those spaces can be constructed and used to rehearse the missions, but how do we ensure their effectiveness? The US Army Research Institute was among the first to demonstrate that spatial knowledge acquired in a virtual model of a building transferred to the real world. While route knowledge was readily acquired in a VE, configuration knowledge (distance and direction to locations not in the line-of-sight) was not. Spatial learning in the VE was hampered not only by disorientation resulting from a narrow FOV and multiple collisions with walls, but also by participants' inability to accurately estimate distances in VEs. Poor distance estimation in VE was linked to the reduced VE FOV and to verbal report procedures for making the estimates. Some improvement in distance estimates was obtained by adding auditory compensatory cues for distance and by using the non-visually locomotion technique for obtaining distance estimates. Armed with knowledge that some VE characteristics adversely affect distance estimation and configuration learning, we conducted research to determine if unique capabilities of VEs could compensate for those characteristics. We developed three VE navigation training aids: local and global orientation cues, aerial views, and division of the VE into distinctive themed quadrants. The aids were not provided when testing configuration knowledge. Training included a guided tour, free exploration of the VE and searching for designated rooms. Configuration knowledge tests included a shortest route test, a pointing task, and a map construction task. An aerial view was the most effective navigation aid, though its effectiveness depended on how it was used. Those participants who used aerial views to organize the VE and learn its layout during free exploration performed quite well, while participants who used it as a crutch to locate a particular destination performed worse than those without an aerial view. To ensure that VEs train effectively, we must recognize VEs' deficiencies, compensate for deficiencies whenever possible, and exploit VEs' unique training capabilities.

Introduction

The U.S. Army has invested heavily in the use of virtual environments (VE) to train combat forces, to evaluate new systems and operational concepts, and to rehearse specific missions. While the Army has focused mainly on simulations for mounted combat, there is also a need to train infantry and other dismounted soldiers. In training dismounted soldiers there are occasions (e.g., rehearsing a hostage rescue mission) in which the soldiers must learn about strategically important spaces to which they have no immediate access. Virtual environments can be constructed as a substitute for these spaces, but how effective are they? This paper describes a series of experiments that investigated the limitations of using VE for training spatial knowledge and how VE might be improved to meet Army human performance goals.

Although VE technologies such as helmet-mounted visual displays, head trackers, 3-D sound systems, haptic devices, and powerful graphics image generators have the potential to immerse dismounted soldiers directly in virtual training environments, their capability to provide effective training has yet to be ascertained. The effective use of VE for training requires more than just VE hardware and software. It also requires a body of knowledge that identifies the characteristics of VE systems that are required to provide effective training and the training strategies and features that are most appropriate for use with VE. In order to develop this body of knowledge, the U.S. Army Research Institute for the Behavioral and Social Sciences (ARI) Simulator Systems Research Unit, initiated a program of experimentation to investigate the use of VE technology to train dismounted soldiers in 1992.

Experiment 1: Transfer of Spatial Knowledge

We were among the first to conduct research demonstrating transfer of spatial knowledge from VE to a real world environment (Witmer, Bailey, Knerr, & Parsons, 1996). For this research, a detailed model of a large office building was constructed using Multigen and World Tool Kit. The model was rendered using a Silicon Graphics Crimson Reality Engine and displayed via a Fake Space Lab Boom. The Boom consists of a high-resolution binocular display on the end of an arm that allowed six degree-of-freedom movement and thumb buttons for controlling forward and backward motion.

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The participants were sixty college students who had no previous exposure to the building. Participants first studied route directions and photographs of landmarks, either with or without a map, then were assigned to one of three rehearsal groups. These were (1) a VE group that rehearsed in the building model, (2) a building rehearsal group that rehearsed in the actual building, and (3) a symbolic rehearsal group that relied on verbal rehearsal of the route directions. Participants were then tested in the real world building for transfer of route training.

Differences in training transfer were evaluated using a MANOVA with rehearsal mode, map, and gender as the independent measures. Only the main effect for rehearsal mode was significant ($p<.001$). A follow-up ANOVA indicated that this effect was significant for each of the dependent measures: route traversal time ($p<.001$); number of wrong turns ($p<.001$); and total distance traveled ($p<.05$). Participants trained in the building made fewer wrong turns ($t=3.25$, $p<.005$) and traveled less distance ($t=2.9$, $p<.01$) than did participants who were trained in the virtual environment (VE). VE participants, in turn, made fewer wrong turns ($t=-4.77$, $p<.001$) and took less time to traverse the route ($t=-5.82$, $p<.001$) than those who were trained symbolically.

In practicing the route, participants were expected to acquire some knowledge about the overall layout of building (i.e., the building configuration). Configuration knowledge was measured using the projective convergence technique (Siegel, 1981; Kirasic, Allen, & Siegel, 1984) and by measuring the capability of subjects to exit the building quickly using an unrehearsed route. The projective convergence technique requires participants to estimate the distance and direction to target locations not in the line of sight, and uses these estimates to determine the participant's perceived target location. The participants either draw lines to indicate the distance and direction to targets (in a non-immersive mode) or point to indicate bearing and verbally report their distance judgments in standard or metric units (in an immersive mode). Errors in estimated bearing and distance using this method may either be due to poor distance estimation skills or disorientation and a lack of knowledge regarding the designated target location. Hence it is not a pure distance estimation measure. MANOVA was used to assess differences in the amount of configuration knowledge. Surprisingly, there were no significant differences among the various rehearsal conditions ($p=.135$) and no significant differences as a function of map use ($p=.688$). Only the effect of gender was significant, with males performing better than females ($p=.015$). No significant interactions were found.

The results suggest that individuals can learn how to navigate a real world route by training in a virtual environment. While the VE used in this experiment was not as effective in training subjects as the actual building, it was much better than verbally rehearsing route directions, even for subjects who had previously studied a map. The effectiveness of the VE for acquiring route knowledge was probably limited by the display reduced field of view and by disorientation after collisions with virtual objects. These factors along with an unnatural interface that controlled movement through the VE. These factors along with participants' inability to judge distance in VEs may also have adversely affected the acquisition of configuration knowledge.

Experiments 2–5: Judging distance in Ves

To better understand why participants were unable to accurately judge distance in the VE, ARI investigators conducted a series basic research experiments in the area (Kline & Witmer, 1996; Witmer & Kline, 1998; Witmer & Sadowksi ,1998). Kline & Witmer (1996) and Witmer and Kline (1998) used magnitude estimation to measure participants' ability to estimate distances in a VE. The task was performed in a virtual office corridor with various floor and wall patterns and textures. Participants first estimated the distance to a standard stimulus (e.g., a cylinder at 100 feet)[2]. They received no feedback regarding the accuracy of their distance estimates to the standard stimulus, but were told that all subsequent estimates should be made relative to that standard. Actual distances varied from 1 to 12 feet in one experiment (Kline & Witmer, 1996), from 10 to 110 feet in another, and from 10 to 280 feet in a third (Witmer & Kline, 1998). The basic measure for all of these experiments, with the exception of Witmer and Sadowski (1998), was the reported target distance in feet or meters. The amount of error in these estimates was calculated as the difference between the estimated and true distance divided by the true distance. This error measurement is called relative error because it is the amount of error relative to the true target distance.

Kline & Witmer (1996) investigated how accurately stationary observers could estimate distance to a wall in a VE as FOV, texture, and pattern were varied. The observer's view was fixed (i.e., no head tracking}. The distances being judged were between 1 and 12 feet. The results indicated that a wider FOV (140H × 90V degrees) produced more accurate estimates than a narrow FOV (60H × 38Vdegrees), $\underline{F}(2,23)=5.85$, $\underline{p}<.01$. Distances were typically underestimated with the wide FOV and overestimated using the narrow FOV. For example, a target placed 5 feet from the observer was judged to be at 2.68 feet with the wide FOV and 8.73 feet with the narrow FOV. Significant two-way interactions of distance with texture, $\underline{F}(44,1054)=2.53$, $\underline{p}<.001$, pattern, $\underline{F}(22,3)=14.1$, $\underline{p}<.05$ and FOV, $\underline{F}(44,1054)=2.5$, $\underline{p}<.001$. indicated that these variables affected depth perception only at the shorter distances.

[2] Note: All distances are given in feet. Multiply by .3048 to convert to meters.

In another experiment, Witmer & Kline (1998) investigated the effects of floor texture and pattern on distance judgements to a cylinder for distances up to 110 feet. The observers were stationary and had a fixed view of the target scene (i.e., no head tracking). Participants grossly underestimated the target distance; the estimates averaged about 50% of the true target distance. This compares to estimates of approximately 75% of the true distance in a comparable real world environment. Cylinder size, $\underline{F}(1,22)=38.67$, $\underline{p}<.001$, distance, $\underline{F}(5,18)=5.87$, $\underline{p}<.01$, and the interaction of cylinder size and distance, $\underline{F}(5,18)=3.97$, $\underline{p}<.05$, significantly affected the magnitude of the VE estimates. The estimates were more accurate for the small cylinder than for the large cylinder. For example, a target placed 50 feet from the observer was judged to be 22.57 feet for the small cylinder and 18.91 feet for the large cylinder. Floor texture did not significantly affect either the distance estimates or the magnitude of the relative errors.

Witmer & Kline (1998) also reported the results of an experiment in which moving observers judged distance traversed for distances up to 280 feet. Half of the participants received compensatory cues (an audible tone every 10 feet) to help them calibrate their distance judgements to the true target distances. Although these cues were provided on only half of the trials, they improved performance to levels approaching perfect performance, $\underline{F}(1,60)=11.49$, $\underline{p}<.001$. The judgments averaged 96% of the true target distance when compensatory cues were present but only 67% of the target distance when compensatory cues were absent. The mode of locomotion used in moving through the VE (treadmill, joystick, or teleport) did not significantly influence the accuracy of the distance estimates, but speed of movement had a significant impact on estimation accuracy, $\underline{F}(1,60)=36.15$, $\underline{p}<.001$. Distance judgments were more accurate at the slow speed than at the fast speed. For example, a distance of 280 feet was judged to be 267 feet on the average when moving at the slow speed and 241 feet when moving at the fast speed. Accuracy of the distance estimates generally decreased as distance to the target increased, $\underline{F}(7,54)=482.53$, $\underline{p}<.001$.

The extremely poor VE distance estimates made by a stationary observer and the lack of substantial improvement in the accuracy of the estimates when observer movement was added (Witmer & Kline, 1998) suggests that either verbal estimates of distance are not very accurate or that VEs degrade distance estimation to a large degree. The ability of participants to accurately report distances in feet or meters varies widely among participants, and may be independent of their perception of target distance. These individual differences may inflate the amount of error observed in estimating target distance. To determine how much of the problem is due to the requirement to provide verbal estimates of distance and how much is due to VE factors, Witmer & Sadowski (1998) used non-visually guided locomotion (NVGL) to obtain distance judgements in VE and real world environments. Participants viewed a target for 10 seconds from a stationary position, forming a mental image of the target's location. They were then blindfolded and asked to walk to the target's location, keeping the target's location in their minds as they approached it and stopping when they thought they had reached it. They were asked not to count steps or time mentally. The distance judgments were performed both in a real world officer corridor and in a virtual office corridor modeled to simulate the real world corridor. The target, a construction cone, was clearly visible and distinct from the background at all distances. Participants made judgements for targets placed at distances between 15 and 105 feet. The distance judgements averaged about 85% of the true target distance in the VE and 92% of the true target distance in the real world environment. The differences between the distance judgements in the VE and in the real world were significant, however, $\underline{F}(1,20)=4.41$, $\underline{p}<.01$. The magnitude of the errors in the VE was nearly twice those obtained in the real world.

Implications of the learning transfer and distance estimation experiments

Our initial investigation of configuration learning (Witmer et al., 1996) suggested that distance estimates in VE were poor. Witmer and Kline (1998) confirmed this, showing that distance estimation in a VE is significantly less accurate than in the real world. Kline & Witmer (1996) demonstrated that reducing the FOV for one of the devices (BOOM2C) could affect not only the amount of error in distance estimates, but also the direction of that error (underestimates vs. overestimates). The hypothesized that narrow FOV produced less accurate estimates by reducing or eliminating linear perspective cues. Witmer & Kline (1998) found that manipulation of textures did little to eliminate the observed deficits in performance. Although target size did influence performance, manipulation of the size of unfamiliar objects is not a practical solution. Taken together, these studies suggest that VEs distort monocular or stereoscopic distance cues, negatively impacting the distance judgements in those VEs.

We had anticipated that providing the cues for distance associated with movement would compensate for the distortion of other distance cues in VE, resulting in substantial improvements in performance. However, Witmer & Kline (1998) found that neither movement method nor edge rate markedly changed the distance judgments. These results indicate that proprioceptive cues and visual flow cues may not play a major role in making distance judgements in a VE. In contrast, movement speed clearly influenced distance judgments, suggesting that the time spent covering a distance changes one's perception of distance traveled. This research also suggested that distance perception in VE could be recalibrated cognitively by providing compensatory cues for distance. This cognitive recalibration may or may not extend to other distances or to other environments, however. Witmer & Kline (1998) did not collect data that would answer questions about transfer of estimating skill to other distances or environments.

Using NVGL to evaluate the accuracy of VE distance estimates altered our working hypothesis regarding how much VE degrades distance estimates. This procedure yielded more accurate VE distance estimates, suggesting that the use of verbal distance estimates is partly responsible for the poor performance observed in our research. However the magnitude of the errors in VE using the NVGL procedure was still twice that observed in the real world, establishing beyond any reasonable doubt that VEs are distorting perceptual judgments of distance.

Factors influencing VE distance judgements

What factors might be responsible for this distortion? In our search for an explanation it is important to remember that the performance decrements were found across various VEs using different display devices, and with varying movement conditions. It is also important to keep in mind the distances investigated in each experiment, because the effective range of various distance cues vary with the distance being judged.

To understand why VE distorts distance perception at the target distances investigated, we need to know which distance cues are effective at those distances, and to assess the extent to which these cues were present or absent in our research. Cutting and Vishton (1995) have identified which depth cues are most effective at different distances and related these cues to three egocentric regions or zones of space: (1) personal space extends just beyond arms reach and refers to space used by a static observer; (2) action space extends to about 100 feet and refers and includes distances in which an observer can throw an object to another person or easily talk to others; and (3) vista space extends beyond 100 feet. Kline & Witmer (1996) studied both personal and action space. In personal space the most important depth cues are occlusion, binocular disparity, relative size, convergence and accommodation. The remaining studies investigated action space and vista space. The primary distance cues in action space and vista space are the pictorial cues, including occlusion, height in the visual field, convergent linear perspective, relative size, and relative textural density. In addition, two other distance cues, binocular disparity and motion perspective are effective distance cues in action space. Note that accommodation and convergence are not effective depth cues in action space or vista space.

Witmer & Kline (1997) have shown that while relative textural density influences distance estimates in VE, its effects are typically too small to account for the differences between real world and VE distance estimation performance. Similarly adding observer movement, which provides motion perspective and other movement related cues does not eliminate the deficits in performance in VEs (Witmer & Kline, 1998). Research by Wright (1995) and Witmer & Kline (1996) suggests that simply using a high resolution or wide FOV VE display cannot erase the deficits in perceived distance. Although occlusion is probably the most powerful depth cue in action space, it was not a factor in our distance estimation tasks. Of the remaining distance cues listed by Cutting & Vishton (1995), height in the visual field, convergent linear perspective, relative size, and binocular disparity appear to be the most likely candidates for explaining the observed discrepancies between VE and real world judgements of distance.

The National Research Council (1997) has suggested that the restricted FOV provided by VE displays must degrade height in the visual field and convergent linear perspective as cues for distance at some point. The limited vertical FOV found in most VE displays (ranging from 40 to 90 degrees) may be responsible for this degradation. By comparison, the real world vertical FOV is approximately 120 degrees. A reduced vertical FOV may result in distant objects appearing closer in VE than they would in the real world because these objects would be compressed into a smaller visual frame as they recede into the distance. Kline & Witmer (1996) showed that a reduced horizontal FOV could also adversely impact the accuracy of distance estimates by reducing or eliminating linear perspective cues. Because linear perspective cues are among the most effective distance cues in simulated environments (Surdick et al., 1997), reducing or eliminating these cues can have a major impact on the accuracy of distance estimates.

In VEs, emulation of binocular disparity is achieved by presenting different images to the two eyes with some central area overlap. While this technique may provide the illusion of depth in VE, it may not faithfully reproduce real world depth. Cutting & Vishton (1995) noted that early stereoscopic pictures enhanced the distance between the eyes to show large expanses and cityscapes, diminishing the effective size of the objects seen. Relative size may be important factor at the closer distances because the perceived size of an object accelerates as the distance to the object decreases, yielding a looming effect. Accommodation and convergence cues are not accurate in VEs, a fact that researchers often use to explain poor distance estimation in VEs. However, these cues are only important for judgments in personal space and at the shorter distances within action space.

Additional research is needed to determine which of the distance cues operating in action space are most responsible for degrading distance judgements in VE. Once the causes of this degradation are isolated, we can begin working toward a solution. The solution may be as simple as increasing the VE display vertical or horizontal FOV, or adjusting the overlap in VE stereoscopic viewing devices. On the other hand, it may involve major technological advances, such as inventing new techniques for emulating binocular disparity in VE displays.

Having identified some of the factors that affect distance judgements in VE, we turned our attention back to how to best use VEs for training configuration knowledge. Our approach was to utilize unique capabilities of VE that might compensate for its inherent deficiencies (e.g., VE's tendency to distort distance judgements).

Enhanced VEs for spatial knowledge acquisition
A computer model of one floor of a large office building, used in previous research (Bailey & Witmer, 1994; Witmer et al., 1996) was adapted for this experiment. All passageways in the virtual building were widened to reduce collisions, an improved collision detection algorithm was introduced that decreased the need to back away from objects following a collision, and additional rooms were modeled. Separate VE models were constructed to represent the standard and enhanced environments. The enhanced environment was created by adding theme objects and sounds to the standard environment model. The models were created using Multigen II software and rendered by a Silicon Graphics Onyx with eight 200MHz processors and three RealityEngine2 Graphics Pipes. Both models were displayed using a Virtual Research V8 Helmet-Mounted Display (HMD). Locomotion through the VE was achieved by virtual walking in the safety pod shown in Figure 1. Head and body movements were independently tracked.

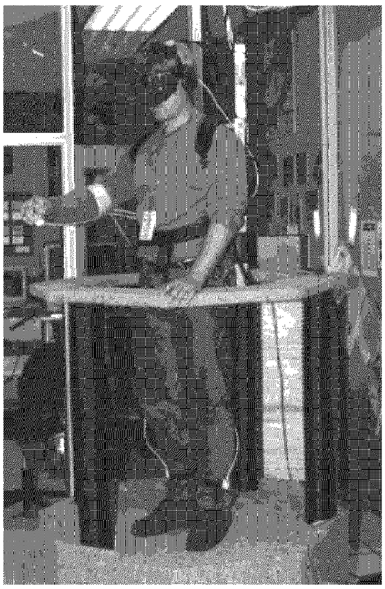

Figure 1: Safety Pod for Virtual Walking

The participants were sixty-four college students who had no previous exposure to the building. Following a brief train-up, the participants were randomly assigned to one of eight treatment groups, who received different levels of navigation aids. Depending on group assignment, a participant experienced either the standard or enhanced VE, received orientation cues or did not, and could chose to view the VE from an aerial perspective or was restricted to viewing the VE from the normal perspective. Orientation cues included an arrow projecting from the chest of the participant's avatar and a flagpole visible throughout the environment.

Groups having an aerial perspective could view the VE from heights of 49, 98, and 394 feet for a period of up to one minute. After one minute, they automatically returned to the normal perspective view. The viewing heights were selected such that participants could see either the whole third floor layout at once at 394 feet or parts of the layout at 39 and 98 feet. More objects in the environment could be recognized at the lower viewing heights. Figure 2 shows the VE from a viewing height of 98 feet. While in the aerial mode participants could further explore the environment by flying to other aerial locations (accomplished by walking in place). To return to ground level they pressed the thumb button on their hand controller, and gradually descended to reenter their virtual body at the exact location where they left it when they started to fly.

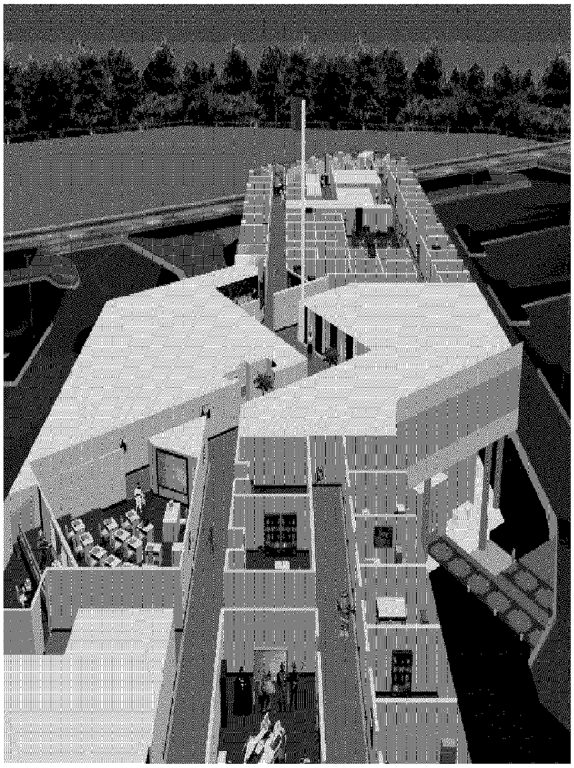

Figure 2: Aerial View of Third Floor Viewed at 98 feet

The enhanced environment model was divided into four themed quadrants or districts. Groups exposed to the themed environment encountered sights and sounds associated with the themed quadrants. Each destination had a memorable theme object located inside the room and an associated sound that became louder as the participant approached the destination room. Additional theme objects were positioned along the building corridors, but no sounds were associated with these additional objects. The themes embedded in the quadrants were a tropical island theme, a wild animals theme, an extraterrestrial (or outer space) theme, and a sports theme. Upon encountering a theme object located inside one of the destination rooms, participants were asked to identify the theme represented by that object. This encouraged participants to associate destination rooms with their location in a particular quadrant.

The orientation cue groups were asked to relate their current position to their starting position marked by a virtual flagpole. This was accomplished by facing the flagpole upon reaching each destination. The flagpole served as a global orientation cue that allowed participants to continually update their current position based on their known starting position. Participants were told to use the arrow projecting from the chest of their avatar as an indication of their current heading and as a way of aligning their virtual body so as to avoid collisions with walls and doorways.

Individual training and testing phases comprised the research. During the first training phase participants followed a virtual tour guide through the VE, pausing at each destination room, and identifying it by name. The tour guide verbally described the 'non-theme related' distinguishing features of each destination. In the second training phase, participants explored the VE freely, while trying to locate and identify each previously visited destination. In the final training phase, participants attempted to take the shortest route from the third floor lobby to each named destination. If the participants did not find the destination within three minutes, they were verbally guided to it. Knowledge of the building configuration was tested by asking participants to complete the following tasks: (1) take the shortest route between designated rooms, (2) estimate the distance and direction to locations not in the line-of-sight, and (3) place room cutouts in their correct locations on a map. Similar to the NVGL procedure, participants estimated distance by walking the straight-line distance between their current location and the perceived location of the destination without vision. Navigation aids were not provided during the testing phase. A follow-up room placement test was given one week after the initial test to examine retention of configuration knowledge.

The purpose of the navigation aids was to offset the effects of VE deficiencies that interfere with the acquisition of configuration knowledge in a VE. The orientation cues had no significant effects on configuration knowledge acquisition, $F(4,51)=2.05$, $p=.10$. Participants receiving the enhanced environment performed better during training than those who received the standard environment, $F(4,51)=2.80$, $p<.05$, but not on the tests of configuration knowledge. Only the participants who received an aerial perspective view performed significantly better both during training, $F(4,51)=5.69$, $p<.001$, and on the configuration knowledge tests, $F(6,50)=3.44$, $p<.01$. Participants with an aerial view during training also performed better on the 1-week retention test, $F(1,51)=9.76$, $p<.01$.

The effectiveness of the navigation aids, including the aerial view, seemed to depend on how the participants used the aids. When the aids were used as a crutch to quickly find a room, they were not effective. Similarly in those cases where the navigation aids increased the workload beyond what the participants could handle, no performance gains were realized. The navigation aids seemed to work best when participants were able to use them to mentally structure the environment. For additional discussion of the effects of these navigation aids, see Witmer, Sadowski, and Finkelstein (in press).

Conclusions

What then must be done to ensure that training in virtual environments meets military human performance goals? The first step is identify the shortcomings of VE that adversely affect VE training effectiveness and link these shortcomings to specific performance deficiencies. For example, in spatial learning, a reduced FOV in VE was linked to poor distance estimation and spatial disorientation, ultimately impairing the acquisition of route and configuration knowledge. The next step is to determine if the deficiency can be addressed directly, or if not, how to compensate for the deficiency. Currently increasing the FOV for VE displays is an expensive proposition and large FOV devices may sacrifice resolution for the larger FOV. We used auditory cues to compensate for poor distance estimation in the VE and showed that the estimates were improved even when the cues were not present. We adopted the NVGL procedure to reduce the affects of individual differences on distance estimation tasks, and used it to measure distance in the projective convergence test. We took steps to reduce collisions in VE, thereby reducing the amount of disorientation that occurred with a narrow FOV display. We also increased the effective FOV by providing participants with an aerial view leading to improved acquisition of configuration knowledge. In searching for effective compensatory mechanisms, some promising factors had little practical effects. A more realistic walking interface (i.e., a treadmill) did not improve distance estimates and dividing the environment into themed quadrants or districts did not improve the performance on tests of configuration knowledge. This demonstrates the importance of evaluating VE interfaces and training enhancements in controlled experiments before implementing them in military training environments.

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